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Fluctuations of the vertical wind as measured by Doppler-SODAR

G. PETERS, M. LATIF, Hamburg, and W. J. MÜLLER, Hannover

Summary. The standard deviation of vertical wind fluctuations in the lower atmosphere can be used as dispersion parameter and be determined by the Doppler-SODAR technique. It can be derived from the width of the average spectra of the scattered signal. The measuring technique is explained and comparisons with an ultrasonic anemometer are discussed.

Messungen der Schwankungen der vertikalen Windgeschwindigkeit mit einem Doppler-SODAR

Zusammenfassung. Die Standardabweichung von Vertikalwindfluktuationen in der unteren Atmosphäre kann als Ausbreitungsparameter verwendet und mit dem Doppler-SODAR vom Boden aus gemessen werden. Sie kann aus der Breite der gemittelten Spektren des Streusignals abgeleitet werden. Das Meßverfahren wird erläutert und Vergleichsmessungen mit einem Ultraschallanemometer werden diskutiert.

1. Introduction

Turbulence intensity is an essential parameter for the dispersion of matter in the atmosphere. A suitable measure is the standard deviation of the vertical wind component σ_w. It can be determined by a Doppler-SODAR-system from the ground up to some hundred meters altitude. In addition the mean wind vector can be measured by this system. Thus the Doppler-SODAR yields all data, which are required by customary calculation schemes for atmospheric dispersion. The capability of SODAR for the measurement of the mean wind field is well established since several years [1] but little is known about the quality of the second moment [2]. Despite there are Doppler-SODAR investigations of the spatial structure of the vertical wind field [3] which include measurements of the second moment, the usability of SODAR for continuous determination of dispersion parameters on a routine basis has not been demonstrated so far.

In this paper comparisons between the standard deviation of the vertical wind component as measured by a Doppler-SODAR (Rosenhagen) and a sonic anemometer (Kaijo Denki) are presented, which extend over a period of about 65 hours und which cover very different meteorological conditions.

2. Description of equipment

2.1. *Sonic anemometer*

The time delay of sound pulses between a transmitter and receiver which are spaced approximately 20 cm is a measure for the wind component parallel to the sound path. The influence of air temperature and of transducer delay is eliminated by reversing the sound path using the same (reciprocal) transducers. A detailed description of this instrument has been published by Hanafusa et al. [4]. The essential system parameters are given in Table 1.

Table 1. *Characteristic parameters of the sonic anemometer*

Measuring path	length	20 cm
	direction	vertical
Sample rate		20 s^{-1}
Measuring range		± 10 m/s
Resolution		2 cm/s

This type of instrument has been selected due to its very stable calibration and its insensitivity to severe environmental conditions.

2.2. *Doppler-SODAR*

The Doppler-SODAR is an acoustic remote sensing system for the lower atmosphere. Sound pulses are transmitted into the atmosphere with a repetition period of some seconds.

Small scale inhomogeneities of the acoustic refractive index which are always present in the atmosphere to more or less extent cause a diffuse scattering of the sound. As the scatter centers are advected by the wind, the frequency of the scattered signal exhibits a Doppler-shift δf. The relation between δf and the wind component u_p parallel to the sound beam is given by

$$u_p = \frac{c}{2} \cdot \frac{\delta f}{f} + 0\,(u/c) \tag{1}$$

with c and f being the sound speed and the transmit frequency respectively. 0 (u/c) are terms of higher order with respect to the normalized wind speed u/c which can be

Table 2. *System parameters of the Doppler-SODAR*

Sound frequency	1675 Hz
Pulse width	100 ms
Pulse repetition rate	9 s
Acoustic transmit power	50 W
3 dB beam width of sound antenna	± 5°
Measuring range (vertical wind component)	± 12 m/s
Averaging time	10 min

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neglected. Thus a vertically pointing sound antenna measures the vertical wind component [3].

The essential parameters of the Doppler-SODAR are given in Table 2.

3. Determination of σ_w by Doppler-SODAR

There are two essentially different ways to process the SODAR-signal in order to exact σ_w. The most straight forward way is to take as many samples as possible of the instantaneous vertical wind w. The second moment of the corresponding distribution is identified with σ_w. But this procedure is not applied here for the following reasons:

The Doppler-shift is a measure for a volume average of w over the total scattering volume which has a characteristic length scale of some ten meters. This averaging acts like a low pass filter and cuts a considerable part of the turbulence spectrum. In order not to reject even more of the turbulence spectrum, instantaneous scatter signals of each individual transmit pulse have to be Doppler-processed. In conditions with low signal-to-noise ratio, which have always to be taken into account in a noisy environment, the estimate of the Doppler-shift contains a considerable unavoidable random error which yields a broadening of the resulting w-distribution. This broadening represents an overestimate of σ_w, which is difficult to be compensated for.

The alternative procedure, which is preferred here, averages the power spectra of the scatter signals of all transmit pulses (here: 66) during the averaging interval.

Additionally measurements of background noise are performed immediately before each transmit pulse. After completion of the averaging time the average background noise spectrum is subtracted from the average signal-plus-noise spectrum. This noise reduction technique is applicable for average spectra only rather than for instantaneous spectra due to statistical reasons. In the following the second moment of the frequency spectrum is identified with its band-width B.

The scatter signal has not a single Doppler-shift frequency but a frequency spectrum of finite width. The main reasons for this broadening are:

a. The altitude of the scattering volume is derived from the time delay with respect to the transmit pulse. As well known from Radar techniques, the relation between signal band-width B_a and heigth resolution δh is

$$B_a = c / \delta h \tag{2}$$

δh is determined by the width of the transmit pulse and of the range gate respectively. Thus B_a is a fixed system parameter.

b. Inside the scattering volume there are "sub scale" turbulent motions. They don't produce a mean Doppler-shift but they cause a Doppler-broadening of the scatter signal, which according to Ford and Meecham [5] is:

$$B_b = \frac{2f}{c}\sqrt{<(w - <w>)^2>} \tag{3}$$

w is the vertical component and <> the scattering volume average.

c. The acoustic antenna has a finite beam width. Scatter centers outside of the zenith, which are advected by the horizontal wind, cause a Doppler-shift according to their zenith and azimuth angle. The corresponding spectral broadening has been analysed theoretically by Brown [6].

d. The acoustic path length between sounder and scattering volume depends on atmospheric parameters. The time dependence of these parameters effects a modulation of the sound and thus a spectral broadening B_d of the scatter signal which has been analysed theoretically by Brown and Clifford [7].

e. The average spectrum is broadened relative to the instantaneous spectra due to fluctuations of the wind (scattering volume average). In general the mean vertical wind is nearly zero when averages of 10 min or more are considered. Then the corresponding spectral broadening is given by

$$B_e = \frac{2f}{c}\sqrt{\overline{<w>^2}} \tag{4}$$

where — represents the time average.

Assuming Gaussian shapes of all spectral contributions the total spectral width B is

$$B = \sqrt{B_a^2 + B_b^2 + B_c^2 + B_d^2 + B_e^2} \tag{5}$$

B_c and B_d depend on the meteorological conditions in a complicated way, but one can conclude from [6] that their contributions can be neglected under all practical atmospheric conditions with the system parameters of the Rosenhagen SODAR. The remaining band-width

$$B_o = \sqrt{B_b^2 + B_e^2} \text{ is}$$

$$B_0 = \frac{2f}{c}\sqrt{\overline{w^2}} = \frac{2f}{c} \cdot \sigma_w \tag{6}$$

σ_w is the desired standard deviation of the vertical wind. A very wide range of scales contributes to this result. The lower limit is given by the wavelength of sound and the upper limit by u · T, where u and T are the mean wind speed and averaging time respectively.

4. The experimental set up

The comparisons were performed in April 1982 in northern Germany close to the town of Stade. The sonic anemometer was mounted on the top of a 40 m mast after calibration in the wind channel of the Meteorological Institute. The standard deviation was calculated on-line in the conventional way using the digitized instantaneous values. The mobile Doppler-SODAR of the NLVA which is normally used for control measurement on a routine basis was put 50 m west of the mast. The wind direction varied between 220 and 320 degrees during the measuring period. One period of 21 hours contained anticyclonal conditions with low winds,

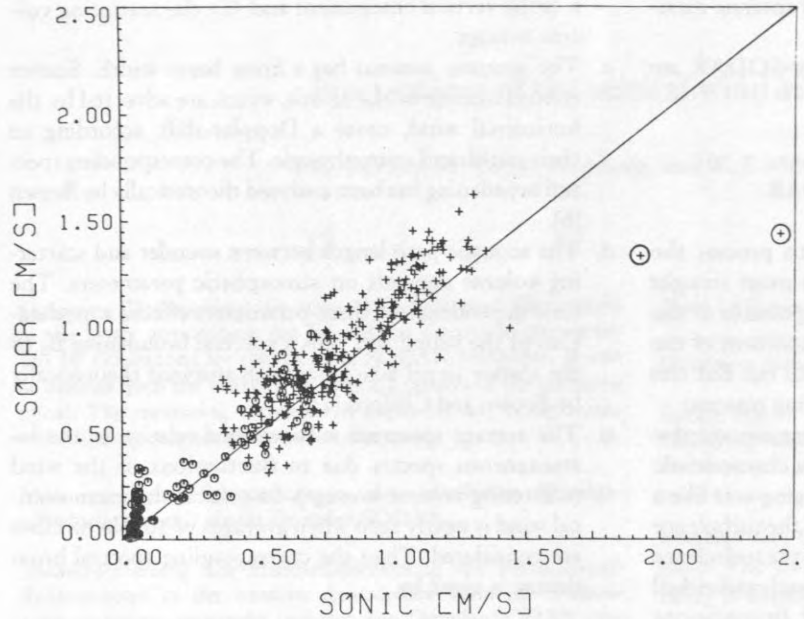

Fig. 1. Standard deviation of the vertical wind as measured with Doppler-SODAR and sonic anemometer +: strong wind period ($\bar{v}$ = 13 m/s) 0: Low wind period ($\bar{v}$ = 3 m/s).

Fig. 2. Time series of the standard deviation σ_w ----: Doppler-SODAR, —: Sonic anemometer.

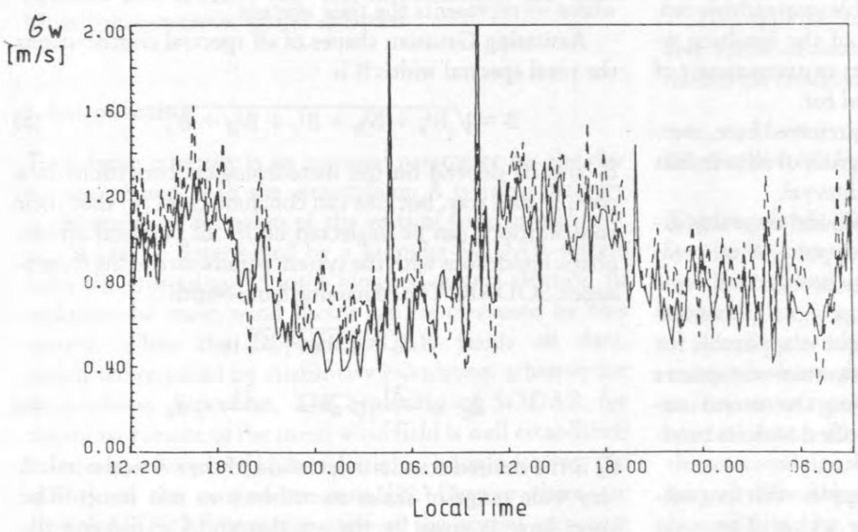

Fig. 2a. Strong wind period $\bar{v}$ = 13 m/s, showers.

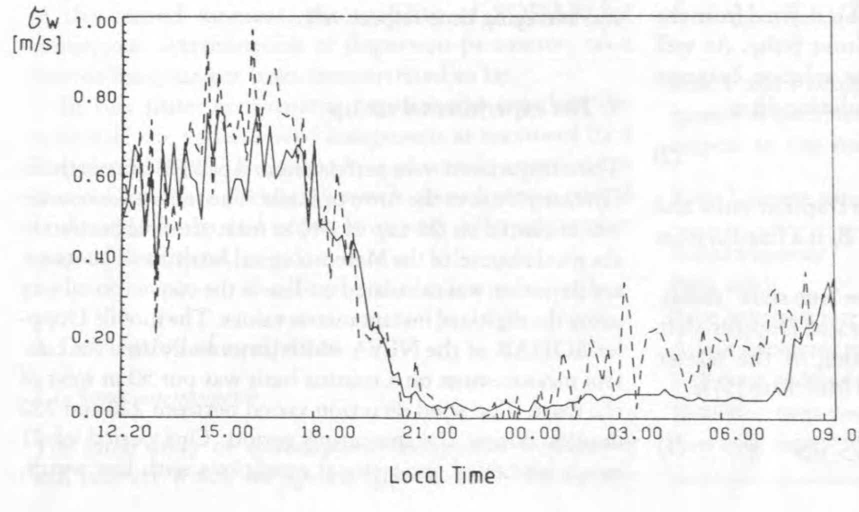

Fig. 2b. Low wind period $\bar{v}$ = 3 m/s.

radiation inversion during the night and correspondingly pronounced change of turbulence intensity from day to night. The mean wind speed during this time was only 3 m/s. Another period of 44 hours was characterized by strong winds with heavy gusts and snow pellet showers. The mean wind speed over this period was 13 m/s. The results of this period are particularly interesting as strong wind and precipitation may cause difficulties for both measuring techniques: Wind noise at the SODAR antenna and falling snow pellets which hit the microphones reduce the signal to noise ratio of the scatter signal and droplets at the transducers of the sonic anemometer modify the acoustic path length.

5. Results

In Fig. 1 the regressions of both measuring periods are shown. The correlation coefficient of the combined periods is 0.92. Despite of the extreme meteorological conditions no significant deviation of the 45 degree axis can be recognized in either measuring period. Two of the 400 points are far off this axis and have been marked by circles. They can be found in the time series in Fig. 2a. At 4.30 and 10.00 both the Doppler-SODAR and the sonic anemometer show very sharp maxima of σ_w which are represented by only one averaging interval. We have no interpretation for these events but we exclude measurement errors as two completely independent spatially separated measuring techniques show these peaks. On the other hand the quantitative difference in peak height as measured by SODAR and sonic anemometer is to be expected for such kind of instationary events and can not be assigned to technical failures. In the early morning of the second measuring period significant differences appear for a longer time. The onset of turbulence at the sonic anemometer is later and much more abrupt than at the SODAR. Even this difference is not necessarily due to a failure of one of the measuring techniques. At least one part of the deviation can be explained by the fact, that the SODAR-data represent volume averages which extend over approximately 20 m height level in contrary to the sonic which samples a volume of 20 cm height extension. The process which produces these different results may be an increasing turbulent layer which fills the scattering volume of the SODAR more and more corresponding to a smoothly growing σ_w. Finally this turbulent layer reaches the altitude of the sonic anemometer and causes a jump of σ_w there.

6. Concluding remarks

The sonic anemometer and the Doppler-SODAR not only yield the same diurnal variation of σ_w but even high-frequent time variations of σ_w are surprisingly well correlated. No significant disagreement was observed even during severe weather conditions.

The strong variability of σ_w from one averaging interval to the next is probably due to low-frequent contributions to the turbulence spectrum. This variability suggests that more than 10 min averaging time seems to be desirable at least for convective conditions.

According to these experiments one may expect that Doppler-SODAR-sounding is a reliable technique to determine atmospheric dispersion parameters even on a routine basis.

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Dr. G. Peters, M. Latif
Meteorolog. Institut
der Univ. Hamburg
Bundesstr. 55
D-2000 Hamburg 13

Dipl.-Met. W. J. Müller
Inst. f. Arbeitsmedizin,
Immissions- u. Strahlenschutz
im Niedersächsischen
Landesverwaltungsamt (NLVA)
Postfach 107
D-3000 Hannover 1

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